

208-W TEM₀₀ operation of a diode-pumped Nd:YAG rod laser

DCC

Y. Hirano, Y. Koyata, S. Yamamoto, K. Kasahara, and T. Tajime

Mitsubishi Electric Corporation, Information Technology Research and Development Center,
5-1-1 Ofuna, Kamakura, Kanagawa 247, Japan

Received January 25, 1999

208-W average-power TEM₀₀-mode operation from a diode-pumped Nd:YAG rod laser was demonstrated. The side-pumping method of generating a high-gain aberration-free rod, the bifocusing-compensation technique with two identically pumped rods, and a suitable choice of beam spot size were employed in the design of this laser. At the maximum pump power of 1.1 kW the fundamental transverse-mode operation ($M^2 < 1.1$) was characterized by 7.6% electrical efficiency. The extraction efficiency was almost 60% of full multimode operation. Stable operation was obtained within a pump-power range of 15% of the maximum pump power.

© 1999 Optical Society of America

OCIS codes: 140.3480, 140.3530.

High-efficiency high-brightness operation of diode-pumped solid-state lasers is attractive for the applications of material processing and remote sensing and as a pump source for frequency conversion. In recent years many high-average-power diode-pumped solid-state lasers^{1,2} have been investigated. One of the topics in this field is how many watts of power these lasers produce in the TEM₀₀ mode. In the high-average-power pumping condition a laser material itself is optically and mechanically distorted by power dissipated as heat. The optical losses in a laser resonator that are caused by these distortions prevent the laser from efficient operation in the TEM₀₀ mode. Three factors limit the TEM₀₀ output power for a Nd:YAG rod laser.

First, thermally induced spatial variation of the refractive index in the Nd:YAG causes the laser rod to act as a lens with a variable focal length. This creates zones of stable TEM₀₀-mode operation. Thermally induced stresses in the isotropic laser rod create birefringence, and the cavity mode is split into two components that are projected along the radial (r) and the tangential (ϕ) axes. Stable TEM₀₀-mode operation can be achieved only in the pump-power range in which the zones for the r - and the ϕ -polarization modes overlap. The overlap zone becomes narrow as the TEM₀₀-mode radius in the rod becomes wide. Murdough and Denman³ demonstrated that the largest TEM₀₀-mode radius that can be supported by a single Nd:YAG rod is approximately 1.1 mm, independent of the physical size of the rod. This maximum accepted mode volume in the rod limits the extracted TEM₀₀ output power from the laser.

Second, deviation from uniform pump distribution causes thermally induced optical aberration in the rod. The transmitted and aberrated wave front from the rod induces diffraction loss in the resonator. The optical efficiency of the laser is essentially determined by the ratio of round-trip optical loss to optical gain. Compared with the increment of rod gain, which is proportional to the pump power, the diffraction loss that is caused by thermally induced aberration increases more rapidly as the pump power increases. The optical efficiency decreases according to the pump power, and consequently the output power is limited.

Third, the fracture strength of the rod places a limit on how hard it can be pumped. This pump-power limitation also limits the output power. Thus, the reported output powers in the TEM₀₀ mode have been limited to the 100-W level.^{4,5}

The first important task in overcoming the TEM₀₀ output power limitation is obtaining a suitable spot size at the mode-selecting aperture of the laser rod for the purpose of maximizing the beam overlap efficiency and minimizing the rod edge-diffraction effect. The separation of the stability zones of polarization modes makes it difficult to obtain an arbitrary spot size. Thus, making the zones of the polarization modes identical is the key technology in overcoming this limitation. The second important task is reducing the influence of laser rod thermal aberrations that cause diffraction loss in the resonator. Considering that the optical efficiency is determined by the ratio of optical loss to gain in the resonator, higher gain and lower aberrations relax the power limitation. Tidwell *et al.*⁴ used an aspheric lens to compensate for these aberrations. However, the compensation is ideally done at a fixed pump power, and consequently the stable operation range of the TEM₀₀ mode is narrow. A pump method that generates a uniform pump distribution in the medium,⁶ coupled with intense pumping of the thin rod, is in our opinion the best approach to this problem. Intense pumping of the thin rod generates high gain, and a uniform pump distribution causes a radial parabolic temperature distribution, resulting in an ideal lens without thermal aberration over a wide pumping range.

A cross section of a high-pump-power module that realizes high gain and low aberration in the Nd:YAG rod is shown in Fig. 1. Twelve 5-bar stacked diode arrays with a cylindrical micrometer array (SDL-3245-J5) with a fourfold symmetrical side-pumping configuration were used. The total diode output peak power was 2.75 kW, with an average power of 550 W. The pulse repetition rate was 1 kHz. For the diode fast axis the output beams from the stacked diode arrays were collimated individually by the cylindrical microlens array and line focused by the aspheric cylindrical lens. To minimize the focusing line thickness we designed the focal length of the aspheric

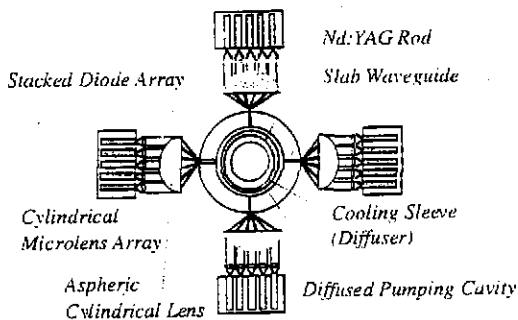


Fig. 1. Cross section of the high-pump-power low-aberration pump module.

cylindrical lens to be 7 mm. The output power from the stacked diode array was power combined in the slab waveguide and then transported inside the diffused pumping cavity through the slab waveguide.⁶ The aperture of the slab waveguide was rectangular, and its width and thickness were 15 mm and 400 μm , respectively. The area of this aperture was only 3.7% of the surface area of the pumping-cavity inner wall. For the 12 stacked diode arrays the averaged transport efficiency from diode output power to power that was incident upon the diffused pumping cavity was 87%. The maximum peak-power line density was ~ 500 W/cm, with an average power line density of 100 W/cm. The reflectivity of the pumping-cavity inner wall, which is made of ceramic, was more than 97%. The circular symmetrical pump beams from the slab waveguides were diffused by the cavity wall and also by the cooling sleeve, which was made of sapphire. The inner surface of the cooling sleeve was ground-rough polished. These reflection- and transmission-type diffusers generated a uniform pump-beam distribution inside the laser rod. Finally, the pump efficiency from the diode-laser output power to the power absorbed by the laser rod was estimated from the measured slope efficiency of full multimode operation. For rod diameters of 4 and 3 mm the pump efficiencies were as high as 72% and 63%, respectively.

The fluorescence distribution, measured at the rod end, was uniform at any pump-power level, and an aberration-free laser rod was expected. To confirm this we measured the wave-front errors for a non-lasing-pumped 3-mm-diameter rod, using a Zygo MarkGPIxp interferometer. The ideal thermal lens (parabolic wave-front error) was removed by use of a defocused telescope, and the residual was removed by means of signal processing. Because of the strong ideal thermal lens we were able to remove the parabolic factor only up to the medium average pump power of 230 W, which is less than half the maximum pumping power of 550 W. Figure 2 shows the pump-power dependence of the peak-to-valley (P-V) and the rms transmitted wave-front errors normalized by the wavelength of 1.064 μm . At the pumping power of 230 W, the increment of rms transmitted wave-front errors (thermal aberration, $\Delta\phi$) is less and 0.004 λ (230 W). Then, at the maximum pump power of 1.1 kW, which we obtained using two pump modules, the cavity round-trip diffraction loss

caused by this thermal aberration is negligible, i.e., $4\pi^2(\Delta\phi)^2 \sim 1.44\%$.

To compensate for the thermal-bifocusing effect of YAG, we considered using the birefringence-compensating technique⁷ with two laser rods. A quartz rotator set between the two laser rods changes the polarization states (radial and tangential) and averages the thermal-lens power for both components. The most important factor in this compensation is that the two laser rods are identically pumped. Figure 3 shows the average diode output-power dependence of the average laser output power for single-module systems (modules 1 and 2) and a dual-module system (module 1 + module 2). Laser rods of 3-mm diameter were placed in resonators of 140-mm (one-rod configuration) and 290-mm (two-rod configuration) length, respectively. The output mirror reflectivity was 57.3%. As shown in Fig. 3, the slope efficiencies were almost identical for single- and dual-module systems, i.e., 34.7%.

Using these pump modules, we demonstrated high average TEM₀₀-mode operation. A schematic diagram of the symmetrical plane-plane oscillator is shown in Fig. 4(a). The simulated shapes of the laser beam in the resonator for both the radial and the tangential components at the highest pump power of 1.1 kW are shown in Fig. 4(b). The propagation of these components is almost identical, and the output beam is well decomposed in the TEM₀₀ mode. To maximize the beam overlap efficiency and minimize the diffraction effects at the laser rod aperture, we designed the

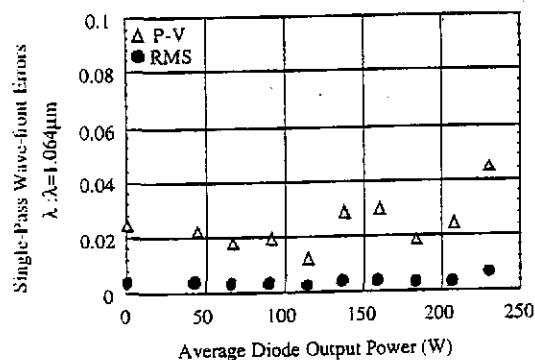


Fig. 2. Single-pass wave-front distortion as a function of diode output power.

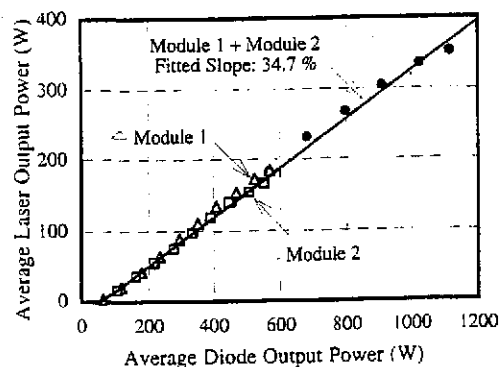


Fig. 3. Average output power as a function of average diode output power in full multimode operation with single- and dual-module systems.

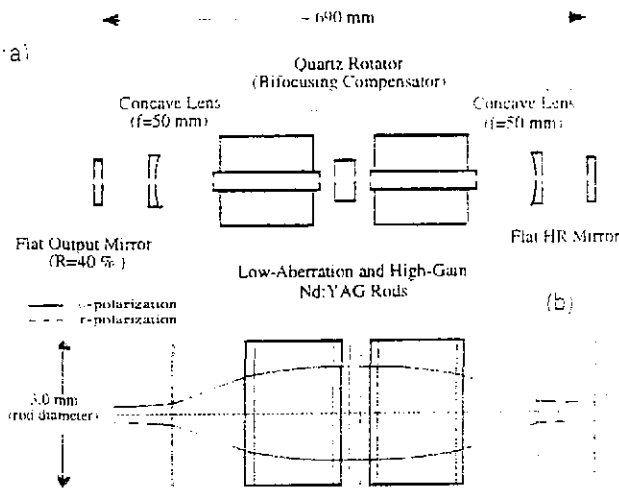


Fig. 4. Schematic diagram of (a) the TEM_{00} -mode laser oscillator and (b) beam propagation in the resonator for both the radial and the tangential components at the highest pump power of 1.1 kW. HR, high reflection.

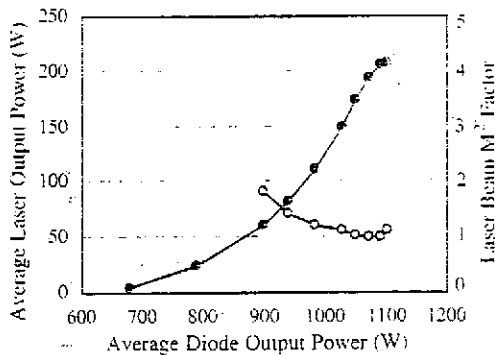


Fig. 5. Average laser output power (filled circles) and laser beam M^2 factor (open circles) dependencies of average laser output power.

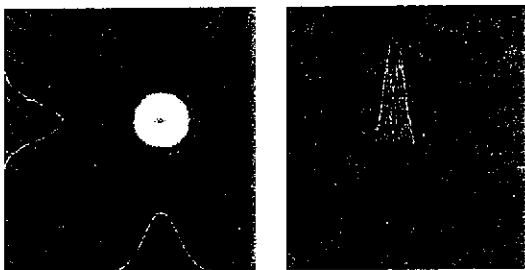


Fig. 6. Two- and three-dimensional laser beam profiles at 208-W output power.

beam radius at the rod end to be $1/1.4$ (~ 1.1 mm) of the rod radius at the highest pump power. Two concave lenses of 50-mm focal lenses were used for this purpose. The high gain of the laser rod allowed us to use an output mirror with 40% reflectivity.

Figure 5 shows the average laser output power and the beam-propagation factor M^2 as a function of the average diode output power. The highest output average power was 208 W at the maximum diode output average power of 1.1 kW. The peak power corresponding to this average power was more than 1 kW. The laser beam M^2 value at this point was less

than 1.1. The optical and the electrical efficiencies were 18.9% and 7.6%, respectively. The output beam profile was well fitted to a Gaussian profile, as shown in Fig. 6. The small deviation from the Gaussian profile is considered to be caused by the low nonuniformity of the fourfold symmetrical pumping configuration. The unpolarized TEM_{00} -mode output power of 208 W is almost 60% of the output power in full multimode operation ($M^2 \sim 50$). TEM_{00} -mode stable operation ($M^2 < 1.5$) was obtained in the pump-power range 940–1100 W (15% of the maximum pump power). This fact surprised us, because the stable pump-power range expected from stability analysis is only $\sim 5\%$ of the maximum pump power. To explain this discrepancy, researchers are studying reduction of thermal loading under conditions of laser extraction.^{8,9} We believe that this reduction of the thermal-focusing effect enlarges the stable zone width, and this effect is attractive for TEM_{00} -mode stable operation of Nd:YAG lasers. In addition, although we have not obtained linearly polarized TEM_{00} -mode operation with an intracavity polarizer, high-gain operation and birefringence compensation, which have the same configuration as bifocusing compensation, are believed to provide highly efficient operation.

In summary, we have demonstrated what is to our knowledge the highest TEM_{00} average output power in the solid-state laser oscillator regime. An average output power of 208 W was obtained, with an optical efficiency as high as 18.9%. The strategy that we used to design this laser was to develop a side-pumping method that generated a high-gain aberration-free rod, employ a two-rod bifocusing-compensation technique, and optimize the beam spot size at the maximum pump power. As aberration-free high-gain laser rods were realized, the output power limitation of TEM_{00} mode was not seen at the power level that was obtained. In addition, we obtained a very large stable-operation pump-power range of 15% of the maximum pump power.

Y. Hirano's e-mail address is hirano@isi.melco.co.jp.

References

1. D. Golla, S. Knoke, W. Schone, G. Ernst, M. Bobe, A. Tunnermann, and H. Welling, *Opt. Lett.* **20**, 1148 (1995).
2. H. W. Bruesselbach, D. S. Sumida, R. A. Reeder, and R. W. Byren, *IEEE J. Sel. Top. Quantum Electron.* **3**, 105 (1997).
3. M. P. Murdough and C. A. Denman, *Appl. Opt.* **35**, 5925 (1996).
4. S. C. Tidwell, J. F. Seamans, and M. S. Bowers, *Opt. Lett.* **18**, 116 (1993).
5. W. Shone, S. Knoke, A. Tunnermann, and H. Welling, in *Conference on Lasers and Electro-Optics*, Vol. 11 of 1997 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1997), paper CPE2.
6. T. Kojima and K. Yasui, *Appl. Opt.* **36**, 4981 (1997).
7. W. C. Scott and M. de Wit, *Appl. Phys. Lett.* **18**, 6 (1971).
8. T. Y. Fan, *IEEE J. Quantum Electron.* **29**, 1457 (1993).
9. S. Guy, C. L. Bonner, B. P. Shepherd, D. C. Hanna, A. V. Tropper, and B. Ferrand, *IEEE J. Quantum Electron.* **34**, 900 (1998).